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At the rainbow's end: high productivity fueled by winter upwelling along an Arctic shelf

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Abstract Herein we document findings from a unique scientific expedition north of Svalbard in the middle of the polar night in January 2012, where we observed an ice edge north of 82°N coupled with pronounced upwelling. The area north of Svalbard has probably been ice-covered during winter in the period from approximately 1790 until the 1980s, a period during which heavy ice conditions have prevailed in the Barents Sea and Svalbard waters. However, recent winters have been characterized by midwinter open water conditions on the shelf, concomitant with northeasterly along-shelf winds in January 2012. The resulting northward Ekman transport resulted in a strong upwelling of Atlantic Water along the shelf. We suggest that a reduction in sea ice and the upwelling of nutrient-rich waters seen in the winter of 2012 created conditions similar to those that

occurred during the peak of the European whaling period (1690–1790) and that this combination of physical features was in fact the driving force behind the high primary and secondary production of diatoms and *Calanus* spp., which sustained the large historical stocks of bowhead whales (*Balaena mysticetus*) in Arctic waters near Spitsbergen.

Keywords Arctic hotspot · Arctic sea ice · Arctic shelf break · *Balaena mysticetus* · Bowhead whales · *Calanus* spp. · Climate change · Ekman transport

Introduction

Vinje's pioneering work published in 1999 (Vinje 1999) documented the location of the minimum ice edge between Svalbard and Franz Josef Land (20–45°E), based on log-books from whalers and early explorers that frequented these waters in late summer and autumn. These data showed that the peak period of European whaling (Fig. 1) coincided with a period of reduced ice extent (approximately 1680–1790), during which the summer ice edge retreated north of 79°N, sometimes as far north as 82°N (Fig. 2). The near extinction of the bowhead whale stock near Svalbard during this time was followed by a period of rapid increase in the extent of summer (August) sea ice commencing around 1790, when the ice edge moved some 500 km southwards to the southern tip of Spitsbergen (around 76°N) within just a few years. This period of heavy summer ice lasted until approximately 1910, after which the ice has again retreated northward (Vinje 1999). Since the 1980s, especially in the past few years, the summer ice edge has once again occurred north of 80°N.

Nutrient-rich water of Atlantic origin is one of the key factors that drive the high primary production that

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Fig. 1 European whaling for bowhead whales off Spitsbergen, Svalbard. http://en.wikipedia.org/wiki/File:Abraham_Storck_-_Walvisvangst.jpg. Abraham Stork, Rijksmuseum Amsterdam

characterizes the Barents Sea (Sakshaug 1997). This level of production in high Arctic waters is the basis for a lipid-driven food chain, from diatoms via *Calanus* spp. to marine mammals and seabirds (Falk-Petersen et al. 1990). In the Svalbard area, nutrient-rich Atlantic Water flows northward along the western Spitsbergen margin (Helland-Hansen and Nansen 1909; Nøst and Isachsen 2003; Walczowski et al. 2005) and descends beneath the fresh, cold Arctic Water at the northwestern tip of Spitsbergen and subsequently flows along northern Svalbard, the European Arctic and Siberian margin at depths between 100 and 400 m. The density gradient between the relatively light Arctic and denser Atlantic Water generally prevents upwelling of the latter (Nansen 1902; Rudels et al. 1999).

In January 2012, we conducted a research cruise to the area north of Spitsbergen during the polar night to study the biological and physical state of the marine ecosystem. During this cruise, we recorded a massive upwelling of warm water of Atlantic origin along the shelf break toward the Arctic Ocean. Upwelling along the shelf break has been predicted by Carmack and Chapman (2003) and Lind and Ingvaldsen (2012) under conditions where a northward retreat of the ice edge relative to the arctic shelf break occurs in combination with favorable along-shelf winds, leading to enhanced offshore Ekman transport. This set of conditions would be expected to support upwelling processes, which would in turn create hotspots of primary

productivity along the shelf break. We suggest that similar upwelling events bringing warm, nutrient-rich Atlantic Water to the surface along the shelf north of Svalbard have occurred in the past—leading to high levels of primary production. This has fueled a *Calanus* spp., lipid-based food chain (Falk-Petersen et al. 2007, 2008), which was the basis for the large historical stock of bowhead whales (*Balaena mysticetus*) in the region.

Methods

In this study, we have compiled data on the late summer position of the ice edge between Svalbard and Franz Josef Land for the period 1553–2012 according to mean latitude in the sector 20–45°E. Some of these data were modified from Vinje (1999, <http://acsys.npolar.no/adis/>), and the data set has been updated to 2012 using monthly mean sea-ice concentration from the National Snow and Ice Data Center (NSIDC, Boulder, USA) (see below).

The January sea-ice extent in Whalers Bay (box bounded by latitudes 80°N and 82.5°N and longitudes 10°E and 30°E), 1979–2012, was calculated using monthly mean sea-ice concentration from the National Snow and Ice Data Center (NSIDC, Boulder, USA). This data set is generated from satellite-based, brightness temperature data derived from the following sensors: the Nimbus-7 Scanning

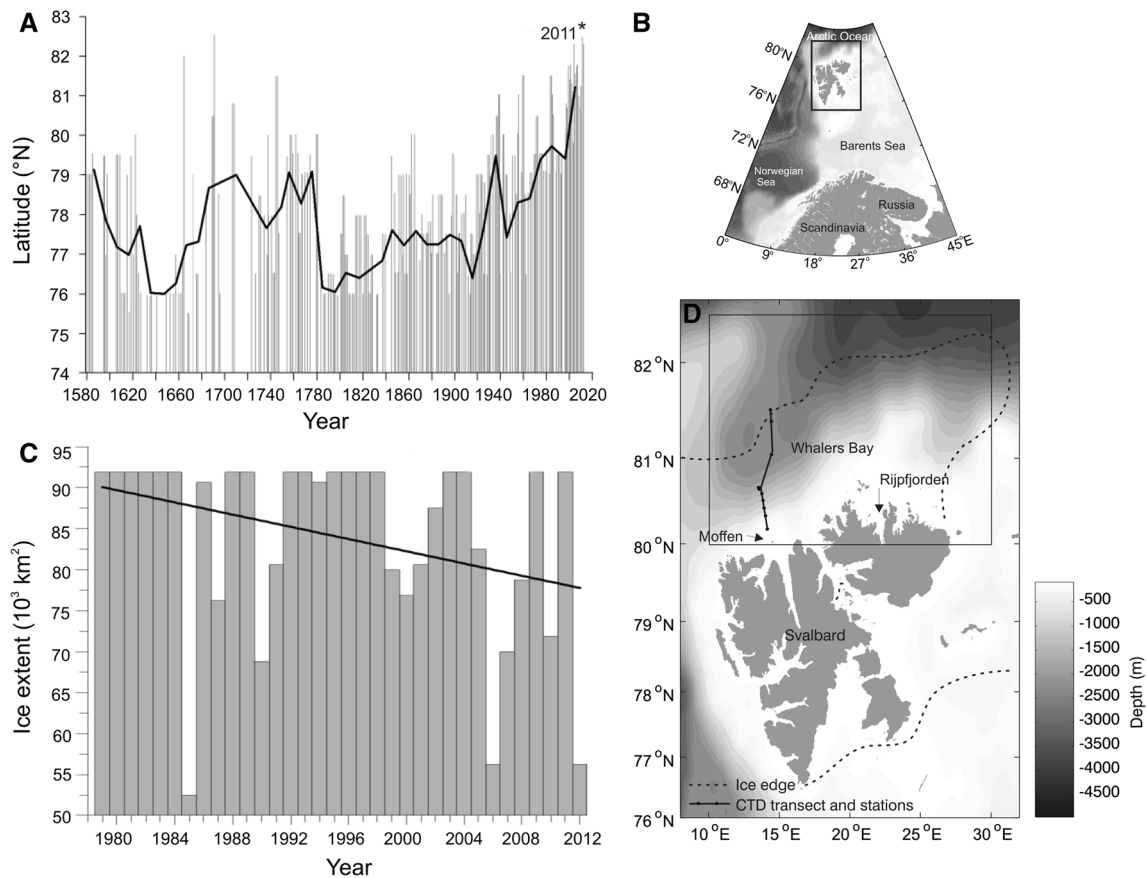


Fig. 2 **a** The position of the ice edge (the gray vertical bars) in August between Svalbard and Franz Josef Land for the period 1553–2012, given as the mean latitude within the sector 20–45°E (modified after Vinje 1999 and updated to summer 2012); solid black line is the 10-year running average; 2011* means the year of the lowest sea-ice extent. **b** The map shows the Barents Sea area, including the Svalbard box. **c** The sea-ice extent (the gray vertical

bars) in Whalers Bay area (box location is presented in Fig. 2d) for the period 1979–2012 in January; solid black line is the linear trend. **d** The map shows the transect (and station sites) north of Svalbard from this study, and locations of box (solid black frame) and ice edges in January 2012. The position of the ice edges was extracted from sea-ice maps produced by Norwegian Meteorological Institute (met. no)

Multichannel Microwave Radiometer (SMMR), the Defense Meteorological Satellite Program (DMSP)-F8, -F11 and -F13 Special Sensor Microwave/Imagers (SSM/I) and the DMSP-F17 Special Sensor Microwave Imager/Sounder (SSMIS). The data are provided in the polar stereographic projection at a grid cell size of 25×25 km for the period 1979–present. For details see http://nsidc.org/data/docs/daac/nsidc0051_gsfc_seaice.gd.html.

Two oceanographic transects across the shelf break, between Rijpfjorden and the ice edge in Sofiadjuet ($81^{\circ}45'N$, $14^{\circ}17'E$) with a return to Moffen ($80^{\circ}06'N$, $14^{\circ}53'E$), were carried out during the Polar Night Cruise with R/V *Helmer Hanssen* to the Whalers Bay area north of Svalbard (Fig. 2b, d) from January 12 to 17, 2012. Salinity, temperature and depth distributions were measured using the calibrated CTD sensors from Sea Bird Electronics, Inc. (SBE) and processed following standard SBE procedures (SBE 911 plus, www.seabird.com).

Reconstruction of sea level pressure (SLP) fields based on monthly mean SLP data (gridded for period 1899–present, with spatial resolution of 5° latitude and longitude) was used. These data were obtained from the Research Data Archive (RDA), which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). The original data are available from the RDA.

Results and discussion

Upwelling

Since the end of the 1980s, the position of the autumn ice edge has been located extremely far north, with open water stretching along the shelf break from northern Svalbard to Franz Josef Land. Such an extreme northerly location of

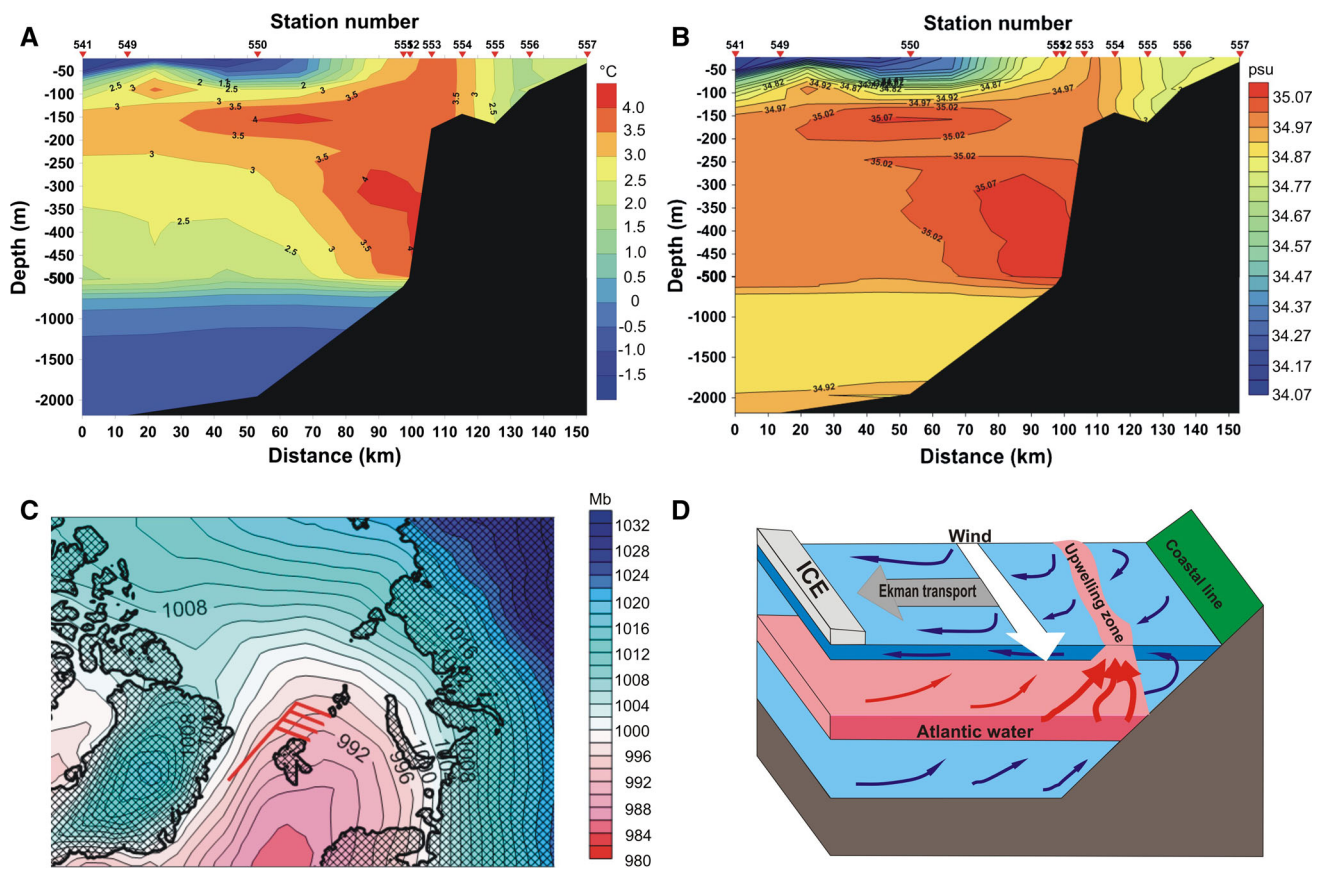


Fig. 3 Upwelling of Atlantic Water north of Svalbard: **a** temperature and **b** salinity distribution along the transect from the ice edge to Moffen Island, 14–16 January 2012. **c** Monthly mean atmospheric pressure field and vector of the northeastern wind (direction -47° ,

velocity 7 m s^{-1}) along the northern coast of Svalbard in December 2011. **d** Schematic of the upwelling process, where along-shelf winds force and Ekman transport of surface water away from the coast allowing deeper Atlantic Water to upwell from below

the ice edge has not been recorded since the period from approximately 1670–1790 (Fig. 2a). During the Polar Night Cruise, the ice edge was as far north as approximately 82°N , and we were able to carry out hydrographic transects across the shelf break in Whalers Bay, from Rijpfjorden to the ice edge, with the return from the ice edge directed to Moffen Island (Fig. 2d). Only oceanographic data from the latter transect, from the ice edge to Moffen is shown, but all transects had very similar hydrographic characteristics, with an upwelling zone of warm Atlantic Water (temperature $3\text{--}4^\circ\text{C}$, salinity ~ 35 psu) stretching from west to east along the northern Svalbard Shelf (Fig. 3). In December 2011 (before the Polar Night Cruise), the area north of Svalbard was largely ice-free and a zone of low atmospheric pressure formed over the Nordic Seas. This atmospheric pressure system led to strong, upwelling-favorable, northeasterly winds along the northern coast of Svalbard, resulting in an Ekman transport toward the north and upwelling of coastal and Atlantic Waters (Fig. 3).

Promoting the lipid-driven food chain of the Arctic

Nutrient-rich water of Atlantic origin drives the high primary production in the Barents Sea (Sakshaug 1997), and this production in high-latitude waters is the basis for a lipid-driven food chain, from diatoms via *Calanus* spp. to marine mammals and sea birds (Falk-Petersen et al. 1990, 2007). The massive upwelling of Atlantic Water observed in January 2012 north of Svalbard is in line with the modeling results of Lind and Ingvaldsen (2012) that winter upwelling of Atlantic Water might occur if the ice edge retreats off the shelf. Using atmospheric hind-cast archived data covering the Norwegian and Barents Seas from 1970 to 2008, these authors showed that the surface wind stress field is generally easterly during winter, resulting in an Ekman transport toward the north along the north coast of Svalbard, which lifts the Atlantic Water slope-current in the Nansen Basin and increases the cross-shelf exchange and the penetration of Atlantic Water onto the shelf. Lind and Ingvaldsen (2012) also showed that Ekman pumping

due to eastern winds is positive everywhere in the area to north of Svalbard.

The role of ice cover in upwelling events is well recognized (e.g., Williams et al. 2006; Pickart et al. 2009; Lind and Ingvaldsen 2012; Schulze and Pickart 2012). Lind and Ingvaldsen (2012) in particular made the point that sea ice, depending on its characteristics, acts to either enhance or reduce the wind momentum transfer to the ocean surface. Although Schulze and Pickart (2012) concluded that in general, the water column response to easterly winds is weakest when the ice cover is near 100 %, but remained mobile. These authors also noted that ice concentrations have been decreasing and that pack-ice has been thinning in recent years. This in turn implies a more unstable pack-ice cover that could lead to increased ice mobility and hence more instances of the maximum upwelling response, such as that documented in the Polar Night Cruise. In comparison with other regions of the Arctic Ocean, the northern Barents Sea and area north of Svalbard display one of the strongest negative trends in sea-ice concentration and also strong positive trends of sea-ice velocities (Pavlov and Pavlova 2008). All of these factors, together with intensification of eastern winds, will create upwelling-favorable conditions in this region.

Sea-ice conditions in the European Arctic are influenced by variability in large-scale atmospheric circulation patterns and ocean currents (e.g., Zhang et al. 2008). However, local air temperature and wind patterns also play a discernible role in determining sea-ice conditions in the northern Barents Sea and in the areas around Svalbard (Schauer et al. 2002; Abrahamsen et al. 2006; Dmitrenko et al. 2009). In particular, local winds can redistribute the sea ice, changing its concentration and affecting ice fluxes from the northeast via the Transpolar Drift system, leading to significant changes in the area to the north of Svalbard (Ådlandsvik and Loeng 1991; Ingvaldsen et al. 2004; Schlichtholz 2011). This area is also characterized by large interannual and decadal variability with respect to sea-ice extent (Vinje 1999) and the overall decline in both sea-ice concentration and sea-ice extent in the Arctic since 1979 are widely documented (e.g., Parkinson and Cavalieri 2008; Comiso et al. 2008; Comiso 2012). Many studies have shown that some of the most dramatic changes have taken place in the northern Barents Sea and in the areas around Svalbard (see e.g., Kvingsedal 2005; Meier et al. 2007; Overland and Wang 2007).

Minimum sea-ice cover in Svalbard waters generally, as well as in Whalers Bay specifically, occurs in August–September. Additionally, it is normal that Whalers Bay does not freeze until midwinter (Falk-Petersen et al. 2000), when the ice forms as a result of two process, the southward expansion of the arctic ice cap and local freezing processes. Whalers Bay has been ice-covered in January

during most winters in the period 1979–1998. However, since 2000, only a few winters have been fully ice-covered in January, with large parts of Whalers Bay being ice-free late into the winter (Fig. 2c). Barber (pers. comm.) has calculated that even if the winter ice cover has not decreased to the same level as the summer minimum, leads and open waters in the arctic winter ice cover occur routinely now, enabling primary production to take place as soon as the sun returns in March/April. We therefore suggest that it is the winter upwelling of nutrient-rich water that supports the massive spring blooms that can take place in leads and open water areas in Whalers Bay during spring in years when the winter ice retreats off the shelf break. Furthermore, we suggest that the rapid expansion of sea ice around 1790 (Vinje 1999) effectively shut down the winter upwelling of nutrient-rich water along the northern shelf break of Svalbard, which in turn limited the potential for recovery of the Spitsbergen bowhead whale stock. The upwelling remained “shut-off” until the late 1990s, when the early winter ice again retreated north of the shelf break in January. The upwelling of nutrient-rich water in this area fuels this local hotspot in Whalers Bay, which attracts lipid-rich high Arctic grazing zooplankton such as *C. finmarchicus*, *C. glacialis* and *C. hyperboreus*. These hypotheses are supported by the high biomass of *C. glacialis* recorded (31 g DWm⁻²) on the northern shelf of Svalbard in recent years (Søreide et al. 2008).

Historical perspective

Bowheads are slow swimmers that feed by filtering zooplankton out of engulfed water masses with their 4.5 to 5-m-long baleen plates. Their main prey is energy-rich *Calanus* spp. (Falk-Petersen et al. 2007), but they also eat other lipid-rich zooplankton that aggregate in upwelling areas (Lowry et al. 2004; Walkusz et al. 2012). Weslawski et al. (2000) estimated, based on a conservative population estimate of 46,000 individuals, that bowhead whales consumed as much as four million tons of plankton per season from June to September in the Svalbard area at the peak of their abundance. Interestingly, this consumption estimate for the bowhead whales of the region represents between 25 and 50 % of today’s standing stock of their principle prey species (Berge et al. 2012, but also see Smetacek 2008). Hence, our argument centers around the fact that previous primary production regimes must have been sufficient to sustain much higher population sizes of these prey species (e.g., *Calanus* spp.) in order for the large stocks of bowhead whales to have thrived. The regional upwelling documented herein provides a hitherto undocumented mechanistic explanation for how such high productivity levels might have been possible.

European whaling commenced in the early 1600 s and was initially focused on the Spitsbergen bowhead whale stock (Fig. 1). The peak of the Spitsbergen whaling period, between 1680 and 1790, coincided with an era during which the minimum (August–September) ice edge was north of 80°N for extended periods, a situation similar to that observed during the last 15 years (Fig. 2). The subsequent near extinction of these whales coincided with a period of rapid expansion of the autumn ice edge from around 1790, when the border of the minimum sea-ice cover expanded some 500 km southwards to around 76°N within a few years (Fig. 2). The Spitsbergen bowhead stock has been estimated to have numbered as many as 100,000 individuals before whaling started (Reeves 1980; Allen and Keay 2006). By the end of the whaling period, around 1800, the Spitsbergen bowhead population had been hunted to near extinction (Woodby and Botkin 1993). The species was very attractive for early whalers; bowheads were valued both for their baleen and for the oil content of their huge blubber deposits, which was used both for human consumption and for lamp oil. The oil was so valuable that Amsterdam ship owners sent their whaling ships northwards into hostile arctic waters northwest of Svalbard for over 100 years.

Future perspectives

In a recently study, a satellite-tagged whale from the Spitsbergen stock followed a migration route between Greenland and Svalbard, identical to that described in historical whaling log books (Lydersen et al. 2012). According to Gray (1931), the distribution of bowhead whales from this stock was historically tightly associated with the pattern of food distribution along the ice edges in the region. Gray described how the whalers searched for areas where the ocean had an opaque green color (caused by diatom blooms), which supported large quantities of *Calanus* copepods which were the main prey for the bowhead whales (Gray 1931). The tagged whale from Lydersen et al. (2012) overwintered in the Fram Strait at about 80°N. This was surprisingly far north and not in accordance with other bowhead whale stocks, or suggestions in the historical literature; most bowhead populations overwinter at the southern parts of their ranges. However, the location of the single whale's track is supported by data from passive acoustic listening devices, which have recorded bowhead whale calls daily throughout the arctic winter at about 80°N in the Fram Strait (Moore et al. 2012; Stafford et al. 2012). During the historical whaling period, no vessels were out in the middle of the Arctic winter searching for whales, and thus, they did not actually know the whereabouts of the bowhead whales during this time of the year. It is likely that Spitsbergen bowhead whales have

used these northern areas as overwintering grounds in the past, similar to today. Recent findings show that *C. glacialis* migrates from depths and gathers in the surface waters (100 m) in March in the Amundsen Gulf (Wold et al. 2011) and as early as mid-January in Svalbard waters (Daase et al. 2013). It makes sense for the whales to take advantage of available food during late winter and early spring during years when the winter ice edge is north of the continental shelf.

The upwelling of Atlantic Water at the shelf edge following the retreat of sea ice north of the shelf in winter might have important implications for the future structure and functioning of the arctic marine ecosystem in the northern Barents Region and beyond. For bowhead whales, this energy source is the treasure at the end of the rainbow that might provide a road to recovery.

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